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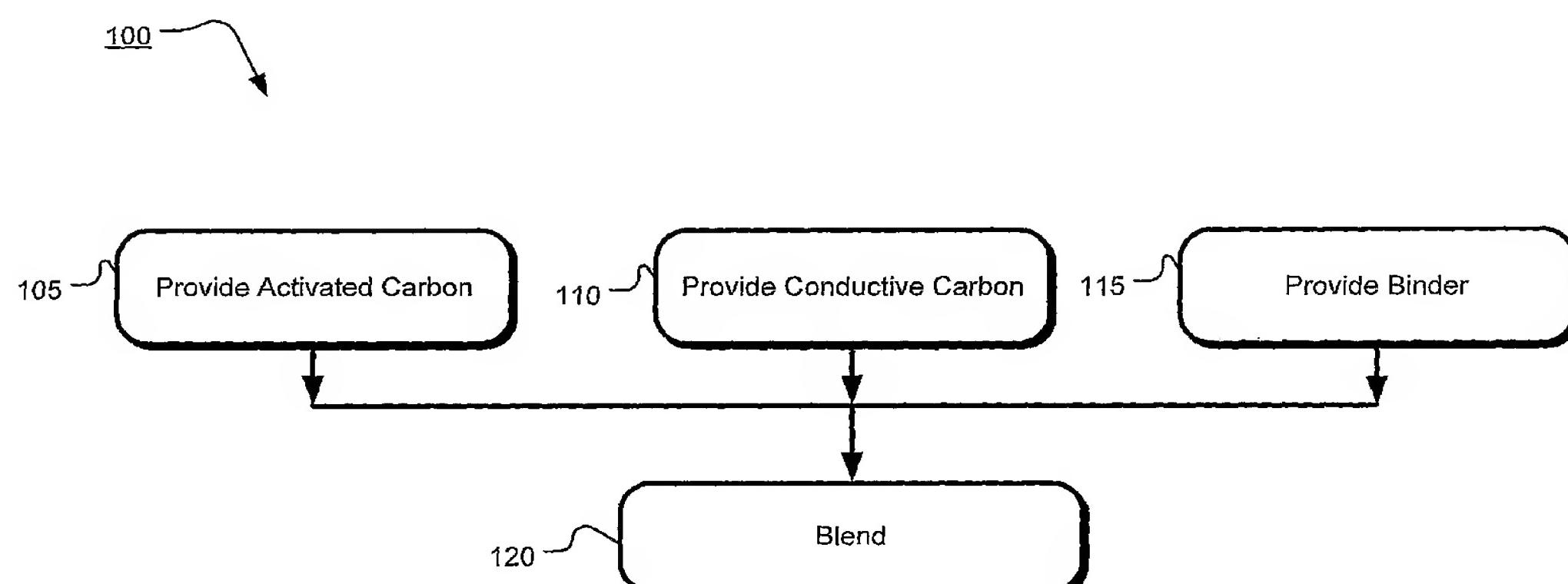
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(54) Title: ULTRACAPACITOR ELECTRODE WITH CONTROLLED CARBON CONTENT



(57) Abstract: An active electrode material is made by blending or mixing a mixture of activated carbon, optional conductive carbon, and binder; wherein the activated carbon has a high soakability to provide a reduced capacitance fade. The electrode material may be attached to a current collector to obtain an electrode for use in various electrical devices, including a double layer capacitor.

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ULTRACAPACITOR ELECTRODE WITH CONTROLLED CARBON CONTENT

BACKGROUND

[0001] The present invention generally relates to electrodes and the fabrication of electrodes. More specifically, the present invention relates to electrodes used in energy storage devices, such as electrochemical double layer capacitors.

[0002] Electrodes are widely used in many devices that store electrical energy, including primary (non-rechargeable) battery cells, secondary (rechargeable) battery cells, fuel cells, and capacitors. Important characteristics of electrical energy storage devices include energy density, power density, maximum charging rate, internal leakage current, equivalent series resistance (ESR), and/or durability, i.e., the ability to withstand multiple charge-discharge cycles. For a number of reasons, double layer capacitors, also known as supercapacitors and ultracapacitors, are gaining popularity in many energy storage applications. The reasons include availability of double layer capacitors with high power densities (in both charge and discharge modes), and with energy densities approaching those of conventional rechargeable cells.

[0003] Double layer capacitors typically use as their energy storage element electrodes immersed in an electrolyte (an electrolytic solution). As such, a porous separator immersed in and impregnated with the electrolyte may ensure that the electrodes do not come in contact with each other, preventing electronic current flow directly between the electrodes. At the same time, the porous separator allows ionic currents to flow through the electrolyte between the electrodes in both directions. As discussed below, double layers of charges are formed at the interfaces between the solid electrodes and the electrolyte.

[0004] When electric potential is applied between a pair of electrodes of a double layer capacitor, ions that exist within the electrolyte are attracted to the surfaces of the oppositely-charged electrodes, and migrate towards the electrodes. A layer of oppositely-charged ions is thus created and maintained near each electrode surface. Electrical energy is stored in the charge separation layers between these ionic layers and the charge layers of the corresponding electrode surfaces. In fact, the charge separation layers behave essentially as

electrostatic capacitors. Electrostatic energy can also be stored in the double layer capacitors through orientation and alignment of molecules of the electrolytic solution under influence of the electric field induced by the potential. This mode of energy storage, however, is secondary.

[0005] In comparison to conventional capacitors, double layer capacitors have high capacitance in relation to their volume and weight. There are two main reasons for these volumetric and weight efficiencies. First, the charge separation layers are very narrow. Their widths are typically on the order of nanometers. Second, the electrodes can be made from a porous material, having very large effective surface area per unit volume. Because capacitance is directly proportional to the electrode area and inversely proportional to the widths of the charge separation layers, the combined effect of the large effective surface area and narrow charge separation layers is capacitance that is very high in comparison to that of conventional capacitors of similar size and weight. The high capacitance of double layer capacitors allows the capacitors to receive, store, and release large amounts of electrical energy.

[0006] Electrical energy stored in a capacitor is determined using a well-known formula:

$$E = \frac{C * V^2}{2} \quad (1)$$

In this formula, E represents the stored energy, C stands for the capacitance, and V is the voltage of the charged capacitor. Thus, the maximum energy (E_m) that can be stored in a capacitor is given by the following expression:

$$E_m = \frac{C * V_r^2}{2}, \quad (2)$$

where V_r stands for the rated voltage of the capacitor. It follows that a capacitor's energy storage capability depends on both (1) its capacitance, and (2) its rated voltage. Increasing these two parameters may therefore be important to capacitor performance.

[0007] Voltage ratings of double layer capacitors are generally limited by electrochemical reactions (e.g., reduction or oxidation) and breakdown that take place within the electrolytic solution in presence of an electric field induced between capacitor electrodes. Electrolytes currently used in double layer capacitors are of two kinds. The first kind includes aqueous electrolytic solutions, for example, potassium hydroxide and sulfuric acid solutions. Double layer capacitors may also be made with organic electrolytes, such as propylene carbonate (PC) solution, acetonitrile (AN) solution, liquid salts commonly referred to as ionic liquids, certain liquid crystal electrolytes, and even solid electrolytes. Voltage ratings of double layer capacitors are also limited by local starvation of electrolyte in the interface of electrolyte and activated carbons, due to the time it takes for the ions to diffuse from the bulk electrolyte to the surfaces of the activated carbons. This local starvation of electrolyte becomes more severe at a high application voltage, since more ions are required for forming the double layer.

[0008] Double layer capacitor cells manufactured using organic electrolytes and activated carbon have typically been rated at or below 2.3 volts in order to achieve a commercially acceptable number of charge-discharge cycles. Even small increases in the rated voltage above 2.3 volts tend to reduce substantially the number of charge-discharge cycles that the capacitors can withstand without significant deterioration in performance. As an approximation, every 100 millivolt increase in the rated capacitor voltage results in halving the number of charge-discharge cycles that the capacitor can reliably withstand.

[0009] It would be desirable to increase actual breakdown voltage of electrolyte in electrical devices with porous electrodes, such as double layer capacitors. It would also be desirable to improve reliability and durability of double layer capacitors, as measured by the number of charge-discharge cycles that a double layer capacitor can withstand without a significant deterioration in its operating characteristics. Some supercapacitors are designed for as many as one million cycles of cycling life. Moreover, capacitance fades during the cycling lifetime due to cell structure and electrode properties. Capacitance fade contributes to a lessening of the life performance of cells and the usable energy of the cell during service. It would thus be further desirable to provide electrodes with less capacitance fade for high performance supercapacitors. A need also exists for methods and materials for making such porous electrodes, and for electrical devices, including double layer capacitors, using such electrodes.

SUMMARY

[0010] Various implementations hereof are directed to methods, electrodes, electrode assemblies, and electrical devices that may be directed to or may satisfy one or more of the above needs. A disclosed exemplar implementation provides a method of making active electrode material. In accordance with such a method, particles of activated carbon, optional conductive carbon, and binder may be mixed. In aspects hereof, the activated carbon may be selected from a variety of activated carbon types. In aspects hereof, activated carbon types may be combined in controlled amounts or ratios for increased performance.

[0011] In accordance with some alternative aspects hereof, the activated carbon may be between about 80 and about 97 percent by weight. Typically, the binder is an electrochemically inert binder, such as PTFE. The proportion of the inert binder may be between about 3 and about 20 percent by weight, and in some other instances between about 9 and about 11 percent by weight, or may be, for example, about 10 percent by weight. In accordance with some aspects hereof, the proportion of the optional conductive particles in the resultant mixture may be between about 0 and about 15 percent by weight, and in some instances does not exceed about 0.5 percent by weight. In accordance with further alternative aspects hereof, mixing of the activated carbon, optional conductive carbon, and binder may be performed by dry-blending these ingredients. In accordance with some further alternative aspects hereof, the mixing may be carried out by subjecting the activated carbon, optional conductive carbon, and binder to a non-lubricated high-shear force technique. In accordance with still further alternative aspects hereof, films of active electrode material may be made from the particles of active electrode material made as is described herein. The films may be attached to current collectors and used in various electrical devices, for example, in double layer capacitors.

[0012] In one implementation, a method of making particles of active electrode material may include providing activated carbon selected from a variety of carbon types. In another implementation, the activated carbon may be fabricated by selectively combining different types of activated carbon. The method may in some options further include providing conductive carbon particles. In one implementation, the binder may be or may include PTFE. In one implementation, the operation of mixing may include dry blending the

activated carbon, conductive carbon, and the binder. In one implementation, the operation of mixing may be performed without processing additives.

[0013] In one implementation, an electrode may include a current collector; and a film of active electrode material attached to the current collector, wherein the active electrode material may include activated carbon selected from one or more sources or by selectively combining activated carbon types. The active electrode material may include binder. The active electrode material may include conductive carbon particles.

[0014] In one implementation, a method of making particles of active electrode material may include providing activated carbon selected from a variety of carbon types, or fabricated by selectively combining different types of carbon; providing optional low contamination level conductive carbon particles; providing binder; and, mixing the activated carbon, the conductive carbon, and the binder to obtain a mixture.

[0015] In one implementation, an electrochemical double layer capacitor may include a first electrode comprising a first current collector and a first film of active electrode material, the first film comprising a first surface and a second surface, the first current collector being attached to the first surface of the first film; a second electrode comprising a second current collector and a second film of active electrode material, the second film comprising a third surface and a fourth surface, the second current collector being attached to the third surface of the second film; a porous separator disposed between the second surface of the first film and the fourth surface of the second film; a container; an electrolyte; wherein: the first electrode, the second electrode, the porous separator, and the electrolyte are disposed in the container; the first film is at least partially immersed in the electrolyte; the second film is at least partially immersed in the electrolyte; the porous separator is at least partially immersed in the electrolyte; each of the first and second films may include a mixture of activated carbon activated carbon selected from one or more combined activated carbon types. In one implementation, the electrode films further may include conductive carbon. In one implementation, the electrode films further may include binder. In one implementation, the films are attached to respective collectors via a conductive adhesive layer.

[0016] These and other features and aspects of the present invention will be better understood with reference to the following description, drawings, and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Fig. 1 illustrates selected operations of a process for making active electrode material in accordance with some aspects hereof;

[0018] Fig. 2, which includes sub-part Figs. 2A and 2B, illustrates a cross-section of respective electrode assemblies which may be used in an ultracapacitor;

[0019] Fig. 3 illustrates capacitance fade of electrodes made from different activated carbons; and

[0020] Fig. 4 also illustrates capacitance fade of electrodes made from different activated carbons.

DETAILED DESCRIPTION

[0021] In this document, the words "implementation" and "variant" may be used to refer to a particular apparatus, process, or article of manufacture, and not necessarily always to one and the same apparatus, process, or article of manufacture. Thus, "one implementation" (or a similar expression) used in one place or context can refer to one particular apparatus, process, or article of manufacture; and, the same or a similar expression in a different place can refer either to the same or to a different apparatus, process, or article of manufacture. Similarly, "some implementations," "certain implementations," or similar expressions used in one place or context may refer to one or more particular apparatuses, processes, or articles of manufacture; the same or similar expressions in a different place or context may refer to the same or a different apparatus, process, or article of manufacture. The expression "alternative implementation" and similar phrases are used to indicate one of a number of different possible implementations. The number of possible implementations is not necessarily limited to two or any other quantity. Characterization of an implementation as "an exemplar" or "exemplary" means that the implementation is used as an example. Such characterization does not necessarily mean that the implementation is a preferred implementation; the implementation may but need not be a currently preferred implementation.

[0022] The expression "active electrode material" and similar phrases signify material that provides or enhances the function of the electrode beyond simply providing a contact or reactive area approximately the size of the visible external surface of the electrode. In a double layer capacitor electrode, for example, a film of active electrode material includes particles with high porosity, so that the surface area of the electrode exposed to an electrolyte in which the electrode is immersed may be increased well beyond the area of the visible external surface; in effect, the surface area exposed to the electrolyte becomes a function of the volume of the film made from the active electrode material.

[0023] The meaning of the word "film" is similar to the meaning of the words "layer" and "sheet"; the word "film" does not necessarily imply a particular thickness or thinness of the material. When used to describe making of active electrode material film, the terms "powder," "particles," and the like refer to a plurality of small granules. As a person skilled in the art would recognize, particulate material is often referred to as a powder, grain, specks, dust, or by other appellations. References to carbon and binder powders throughout this document are thus not meant to limit the present implementations.

[0024] The references to "binder" within this document are intended to convey the meaning of polymers, co-polymers, and similar ultra-high molecular weight substances capable of providing a binding for the carbon. Such substances may be employed as binders for promoting cohesion in loosely-assembled particulate materials, i.e., active filler materials that perform some useful function in a particular application.

[0025] The words "calender," "nip," "laminator," and similar expressions mean a device adapted for pressing and compressing. Pressing may be, but is not necessarily, performed using rollers. When used as verbs, "calender" and "lamine" mean processing in a press, which may, but need not, include rollers. Mixing or blending as used herein may mean processing which involves bringing together component elements into a mixture. High shear or high impact forces may be, but are not necessarily, used for such mixing. Example equipment that can be used to prepare/mix the dry powder(s) hereof may include, in non-limiting fashion: a ball mill, an electromagnetic ball mill, a disk mill, a pin mill, a high-energy impact mill, a fluid energy impact mill, an opposing nozzle jet mill, a fluidized bed jet

mill, a hammer mill, a fritz mill, a Waring blender, a roll mill, a mechanofusion processor (e.g., a Hosokawa AMS), or an impact mill.

[0026] Other and further definitions and clarifications of definitions may be found throughout this document. The definitions are intended to assist in understanding this disclosure and the appended claims, and the scope and spirit of the invention should not be construed as strictly limited to the particular examples described in this specification.

[0027] Reference will now be made in detail to several illustrations of the invention that are illustrated in the accompanying drawings. The same reference numerals are used in the drawings and the description to refer to the same or substantially the same parts or operations. The drawings are in simplified form and not to precise scale. For purposes of convenience and clarity only, directional terms, such as top, bottom, left, right, up, down, over, above, below, beneath, rear, and front may be used with respect to the accompanying drawings. These and similar directional terms, should not be construed to limit the scope of the invention.

[0028] Referring more particularly to the drawings, FIG. 1 illustrates selected operations of a process 100 for making active electrode material. Although the process operations are described substantially serially, certain operations may also be performed in alternative order, in conjunction or in parallel, in a pipelined manner, or otherwise. There is no particular requirement that the operations be performed in the same order in which this description lists them, except where explicitly so indicated, otherwise made clear from the context, or inherently required. Not all illustrated operations may be strictly necessary, while other optional operations may be added to the process 100. A high level overview of the process 100 is provided immediately below. A more detailed description of the operations of the process 100 and variants of the operations are provided following the overview.

[0029] In one implementation of a process 100, an operation 105 may provide activated carbon particles and in an optional operation 110, optional conductive carbon particles with low contamination level and high conductivity may be provided. In operation 115, binder may be provided. In one or more implementations, and although one or more of a variety of binders may be used as described elsewhere herein, the binder may include polytetraflouoroethylene (also known as PTFE or by the tradename, "Teflon®"). In the

mixing or blending operation 120 hereof, one or more of the activated carbon, conductive carbon, and binder may be blended or mixed; typically two or more may be mixed together, most typically, the activated carbon is mixed with the binder. Alternatively, in certain implementations one of the activated carbon or conductive carbon ingredients and/or operations may be omitted. It should be understood that no implementations are to be limited to particular brands or suppliers of carbon, binder, or other materials.

[0030] Set forth herein are more detailed descriptions of high soaking capacity carbon electrode structures and the processes by which these may be made. It has been found that electrodes made with high carbon soaking capacities have better, that is to say, less capacitance fade than electrodes made with lower respective soaking capacities of the activated carbons thereof. Accordingly, in some implementations hereof the soaking capacities of about one third or more better than a comparable carbon product may provide as much as about 14% less capacitance fade.

[0031] Referring more particularly to FIG. 3, there is set forth an illustration in graph 300 of the capacitance fade of electrodes made from different activated carbons. As illustrated herein, different commercially activated carbon types have different rates of capacitance fade. As further illustrated by this FIG. 3, all the electrodes subjected to the test thereof experienced some degree of capacitance fade. The different activated carbons began the test with capacitance within approximately five (5) percentage points of each other, but ended the test with respective capacitance fades that exhibited a range of approximately 14 percentage points from the activated carbon with the least capacitance fade (denominated C#8 in FIG. 3) to the activated carbon with the most capacitance fade (denominated C#2) (note, an intervening data set for a further alternative activated carbon, denominated C#12 in FIG. 3 has also been provided).

[0032] Through soaking weight testing, it has been observed that the soaking weight of the electrode may correlate with the capacitance fade shown in the graph 300 of FIG. 3. As illustrated in TABLE 1, below, the carbon with the higher soaking weight, when incorporated into an electrode, correlated to less capacitance fade during tests such as the one depicted in FIG. 1.

Table 1. Electrode soaking weight

Sample name	Electrode soaking wt (g/g)
C#8	2.1 +/- 0.1
C#12	1.82 +/- 0.1
C#2	1.48 +/- 0.1

[0033] In some implementations using the process wherein activated carbon selected for its soakability or combined in such a way as to maximize soakability is used, a high performance ultracapacitor or double-layer capacitor product can be provided. Such a product further may include about 10 percent by weight binder, and about 0.5 percent by weight conductive carbon.

[0034] FIG. 4 compares, in graph 400, the capacitance fade of electrodes made from a conventionally available activated carbon with an electrode made from a selected combination or mixture of conventionally available activated carbons. The lower line or trace on the graph corresponds to the commercially available activated carbon C#1. The upper line or trace on the graph corresponds to an activated carbon mixture that includes about 95 percent C#1 and about 5 percent C#8 by weight. As illustrated herein, electrodes incorporating different activated carbon types have different rates of capacitance fades, and that a superior soaking capacity carbon such as C#8 mixed in even a relatively small amount with another carbon, can significantly decrease the capacitance fade of the dominant carbon.

[0035] Though not illustrated in TABLE 1, above, the soaking weight of an electrode incorporating C#1 is about 1.5 g/g. As further illustrated in TABLE 1, the soaking weight of an electrode incorporating C#8 is about 2.1 g/g. By adding a mere 5% of C#8 activated carbon by weight to a C#1 activated carbon electrode (i.e., so that the resulting mixture contains approximately 5 percent by weight of C#8), the electrode soaking weight of an electrode incorporating the resulting mixture increases to between about 1.65 g/g and about 1.7 g/g. And, the two different activated carbons in this FIG. 4 began the test with respective capacitance values within approximately 5 percentage points of each other. At the end of the test, however, the capacitance fade exhibited a range of approximately 12 percentage points

between the substantially pure C#1 activated carbon and the activated carbon that includes about 5 percent C#8 by weight.

[0036] A method for determining electrode soaking weight is also described herein. In one implementation, an electrode sample measuring about 4 cm by 4 cm square may be cut from an electrode fabricated with a pre-selected conventionally available carbon or mixture of conventionally available carbons. The thickness and weight of the cut electrode sample may then be measured and recorded. In a bottle disposed to accommodate the electrode sample, an electrolyte solution may be poured and the weight of the electrolyte solution taken and recorded. The electrode sample may then be placed into the electrolyte solution for a period of approximately 5 minutes, and may be removed at the expiration of this period of time. The weight of the electrolyte solution may then be taken and recorded in the same manner as it was weighed before the electrode sample was soaked. The "soakability" of the electrode sample may then be determined by calculating the weight of the electrolyte soaked by the electrode per gram of electrode. This soakability index may then be used as a guideline for formulation and development of an optimized electrode with optimized soakability. As illustrated herein, the higher the soakability of the electrode, the less the capacitance fade of the electrode.

[0037] More detailed descriptions of individual operations of the process by which electrodes may be created, in alternative forms, are described herein below. As a first example, per operation 105 of FIG. 1, the provision of activated carbon particles selected from a conventionally available type of carbon, is first set forth. As described, electrodes made from activated carbon particles with a higher soakability tend to have less capacitance fade than electrodes made from other types of activated carbon particles with lower soakability. Accordingly, in some implementations the activated carbon particles may be taken from one or a combination of activated carbon types with higher soakability.

[0038] In the further provision of a binder per operation 115 of FIG. 1, to be mixed with the activated carbon selected per operation 105, one or more of a variety of alternative binders may be provided, as for example: PTFE in granular powder form, and/or one or more of various other fluoropolymer particles, or polypropylene, or polyethylene, or co-polymers, and/or other polymer blends. It has been identified that the use of inert binders such as PTFE, tends to increase the voltage at which an electrode including such an inert binder may

be operated. Such an increase may occur in part due to reduced interactions with electrolyte in which the electrode is subsequently immersed. In one implementation, typical diameters of the PTFE particles may be in the five hundred micron range.

[0039] In the mixing process 120, the activated carbon particles and binder particles may be blended or otherwise mixed together in a variety of proportions. In various implementations, proportions of activated carbon and binder may be as follows: about 80 to about 97 percent by weight of activated carbon, about 3 to about 20 percent by weight of PTFE. Optional conductive carbon could be added in a range of about 0 to about 15 percent by weight. An implementation may contain about 94.5 percent of activated carbon, about 5 percent of PTFE, and about 0.5 percent of conductive carbon. Other ranges are within the scope hereof as well. Note that all percentages are here presented by weight, though other percentages with other bases may be used. Conductive carbon may be preferably held to a low percentage of the mixture because an increased proportion of conductive carbon may tend to lower the breakdown voltage of electrolyte in which an electrode made from the conductive carbon particles is subsequently immersed.

[0040] In an implementation of the overall electrode manufacturing process 100, the blending operation 120 may be a "dry-blending" operation, i.e., blending of activated carbon, conductive carbon, and/or binder is performed without the addition of any solvents, liquids, processing aids, or the like to the particle mixture. Dry-blending may be carried out, for example, for about 1 to about 10 minutes in a mill, mixer, or blender (such as a V-blender equipped with a high intensity mixing bar, or other alternative equipment as described further below) until a uniform dry mixture is formed. Those skilled in the art will identify, after perusal of this document, that blending time can vary based on batch size, materials, particle size, densities, as well as other properties, and yet remain within the scope hereof.

[0041] As introduced above, the blended powder material may also or alternatively be formed/mixed/blended using other equipment. Such equipment that can be used to prepare/mix dry powder(s) hereof may include, for non-limiting examples: blenders of many sorts including rolling blenders and warring blenders, and mills of many sorts including ball mills, electromagnetic ball mills, disk mills, pin mills, high-energy impact mills, fluid energy impact mills, opposing nozzle jet mills, fluidized bed jet mills, hammer mills, fritz mills, roll mills, mechanofusion processing (e.g., a Hosokawa AMS), or impact mills. In an

implementation, dry powder material may be mixed using non-lubricated high-shear or high impact force techniques. In an implementation, high-shear or high impact forces may be provided by a mill such as one of those described above. The powder material, binder and carbon, may be introduced into the mill, wherein high-velocities and/or high forces could then be directed at or imposed upon the powder material to effectuate application of high shear or high impact to the binder within the powder material. The shear or impact forces that arise during the dry mixing process may physically affect the binder, causing the binder to bind the binder to and/or with other particles within the material. A dry mixing process is described in more detail in a co-pending commonly-assigned U.S. Patent Application, number 11/116,882. This application is hereby incorporated by reference for all it discloses as if fully set forth herein, including all figures, tables, and claims. It should also be noted that references to dry mixing, dry-blending, dry particles, and other dry materials and processes used in the manufacture of an active electrode material and/or film do not exclude the use of other than dry processes, for example, this may be achieved after drying of particles and films that may have been prepared using a processing aid, liquid, solvent, or the like.

[0042] The mixing process whereby the constituent materials may be mixed as described above may result in a breakdown of the larger polymer binder agglomerates of a pre-mixed binder into smaller polymer agglomerates and/or primary particles. The smaller polymer binder agglomerates and/or primary particles may disperse substantially uniformly throughout the powder mixture resulting in good binding properties for each binder agglomerate or particle and thus also good binding in the mixture.

[0043] A product obtained through such a mixing process may be used to make an electrode film. The films may then be bonded to a current collector, such as a foil made from aluminum or another conductor. The current collector can be a continuous metal foil, metal mesh, or nonwoven metal fabric. The metal current collector provides a continuous electrically conductive substrate for the electrode film. The current collector may be pretreated prior to bonding to enhance its adhesion properties. Pretreatment of the current collector may include mechanical roughing, chemical pitting, and/or use of a surface activation treatment, such as corona discharge, active plasma, ultraviolet, laser, or high frequency treatment methods known to a person skilled in the art. In one implementation, the

electrode films may be bonded to a current collector via an intermediate layer of conductive adhesive known to those skilled in the art.

[0044] In one implementation, a product obtained from the mixing process may be mixed with a processing aid to obtain a slurry-like composition used by those skilled in the art to coat an electrode film onto a collector (i.e. a coating process). The slurry may be then deposited on one or both sides of a current collector. After a drying operation, a film or films of active electrode material may be formed on the current collector. The current collector with the films may be calendered one or more times to densify the films and to improve adhesion of the films to the current collector.

[0045] In one implementation, a product obtained from the mixing process may be mixed with a processing aid to obtain a paste-like material. The paste-like material may be then be extruded, formed into a film, and deposited on one or both sides of a current collector. After a drying operation, a film or films of active electrode material may be formed on the current collector. The current collector with the dried films may be calendered one or more times to densify the films and to improve adhesion of the films to the current collector.

[0046] In yet another implementation, in a product obtained through a mixing process hereof, the binder particles may include thermoplastic or thermoset particles. A product obtained through a mixing process hereof that includes thermoplastic or thermoset particles may be used to make an electrode film. Such a film may then be bonded to a current collector, such as a foil made from aluminum or another conductor. The films may be bonded to a current collector in a heated calendar apparatus. The current collector may be pretreated prior to bonding to enhance its adhesion properties. Pretreatment of the current collector may include mechanical roughing, chemical pitting, and/or use of a surface activation treatment, such as corona discharge, active plasma, ultraviolet, laser, or high frequency treatment methods known to a person in the art.

[0047] Electrode products that include an active electrode film attached to a current collector and/or a porous separator may be used in an ultracapacitor or a double layer capacitor and/or other electrical energy storage devices. Other methods of forming the active electrode material films and attaching the films to the current collector may also be used.

[0048] Fig. 2, including sub-part Figs. 2A and 2B, illustrates in a high level manner, respective cross-sectional views of an electrode assembly 200 which may be used in an ultracapacitor or a double layer capacitor. In Fig. 2A, the components of the assembly 200 are arranged in the following order: a first current collector 205, a first active electrode film 210, a porous separator 220, a second active electrode film 230, and a second current collector 235. In some implementations, a conductive adhesive layer (not shown) may be disposed on current collector 205 prior to bonding of the electrode film 210 (or likewise on collector 235 relative to film 230). In Fig. 2B, a double layer of films 210 and 210 are shown relative to collector 205, and a double layer 230, 230A relative to collector 235. In this way, a double-layer capacitor may be formed, i.e., with each current collector having a carbon film attached to both sides. A further porous separator 220A may then also be included, particularly for a jellyroll application, the porous separator 220A either attached to or otherwise disposed adjacent the top film 210A, as shown, or to or adjacent the bottom film 230A (not shown). The films 210 and 230 (and 210A and 230A, if used) may be made using particles of active electrode material obtained through the process 100 described in relation to Fig. 1. An exemplary double layer capacitor using the electrode assembly 200 may further include an electrolyte and a container, for example, a sealed can, that holds the electrolyte. The assembly 200 may be disposed within the container (can) and immersed in the electrolyte. In many implementations, the current collectors 205 and 235 may be made from aluminum foil, the porous separator 220 may be made from one or more ceramics, paper, polymers, polymer fibers, glass fibers, and the electrolytic solution may include in some examples, 1.5 M tetramethylammonium tetrafluroborate in organic solutions, such as PC or Acetonitrile solvent.

[0049] Electrodes, particularly in many examples, double layer electrodes, have thus herein been shown be fabricated by a process or method, typically dry, by provision of activated carbon with a preferred soaking capacity. An activated carbon with a high soaking capacity or wettability may be selected, or a mixture of a carbon with a high soaking capacity or wettability with a carbon with, for example, good electrical characteristics, e.g., good capacitance, conductivity, low resistance (ESR), high voltage capacity or the like may be chosen. Electrodes made with such controlled carbon provision may then exhibit desired electrical characteristics.

[0050] The inventive methods for making active electrode material, films of these materials, electrodes made with the films, double layer capacitors employing the electrodes, and for testing the soaking weight of electrodes have been described above in considerable detail. This was done for illustrative purposes. Neither the specific implementations of the invention as a whole, nor those of its features, limit the general principles underlying the invention. In particular, the invention is not necessarily limited to the specific constituent materials and proportions of constituent materials used in making the electrodes. The invention is also not necessarily limited to electrodes used in double layer capacitors, but extends to other electrode applications. The specific features described herein may be used in some implementations, but not in others, without departure from the spirit and scope of the invention as set forth. Many additional modifications are intended in the foregoing disclosure, and it will be appreciated by those of ordinary skill in the art that, in some instances, some features of the invention will be employed in the absence of other features. The illustrative examples therefore do not define the metes and bounds of the invention and the legal protection afforded the invention, which function is served by the claims and their equivalents.

CLAIMS

Accordingly, what is claimed is:

1. A method of making an active electrode material, the method comprising:
 - providing activated carbon;
 - providing binder; and,
 - mixing the activated carbon and the binder to obtain a mixture, wherein the activated carbon has a soakability index of about 2 grams of electrolyte per gram of electrode material.
2. A method in accordance with claim 1, wherein the soakability index is between about 1.38 grams of electrolyte/gram of electrode and about 2.2 grams of electrolyte/gram of electrode material.
3. A method in accordance with claim 1, wherein one or both of: the operation of providing the activated carbon includes providing activated carbon in an amount of between about 80 and about 97 percent by weight; and the operation of providing binder includes providing binder in an amount of between about 3 and about 20 percent by weight.
4. A method in accordance with claim 1, further including providing an additional additive component of conductive carbon.
5. A method in accordance with claim 1, wherein the soakability index of the activated carbon is manipulated by adding a second activated carbon component with a different soakability index to the active electrode material.
6. A method in accordance with claim 5, wherein the soakability index of the second activated carbon is higher.
7. A method in accordance with claim 1, wherein the operation of mixing includes dry blending the activated carbon and the binder.

8. A method in accordance with claim 1, wherein the operation of mixing is performed without processing additives.

9. An electrode comprising:

a current collector; and

a film of active electrode material attached to the current collector, wherein the active electrode material is a mixture including an activated carbon component, an optional conductive carbon component, and a binder component;

wherein the activated carbon has a soakability index of about 2 grams of electrolyte per gram of electrode material.

10. An electrode in accordance with claim 9, wherein the soakability index is between about 1.38 grams of electrolyte/gram of electrode and about 2.2 grams of electrolyte/gram of electrode material.

11. The electrode of claim 9, wherein the active electrode material includes activated carbon and a binder, wherein the activated carbon content is in an amount of between about 80 and about 97 percent by weight, and wherein the binder is in an amount of between about 3 and about 20 percent by weight, and the activated carbon has a soakability index of between about 1.38 grams of electrolyte/gram of electrode and about 2.2 grams of electrolyte/gram of electrode.

12. An electrode in accordance with claim 9, wherein the soakability index of the activated carbon is manipulated by adding a second activated carbon component with a different soakability index to the active electrode material.

13. An electrode in accordance with claim 12, wherein the soakability index of the second activated carbon is higher.

14. The electrode of claim 9, wherein the active electrode material is formed from a mixture of activated carbon and binder, the mixture formed through mixing with a dry process.

15. An electrochemical double layer capacitor comprising:

a first electrode comprising a first current collector and a first film of active electrode material, the first film comprising a first surface and a second surface, the first current collector being attached to the first surface of the first film;

a second electrode comprising a second current collector and a second film of active electrode material, the second film comprising a third surface and a fourth surface, the second current collector being attached to the third surface of the second film;

a porous separator disposed between the second surface of the first film and the fourth surface of the second film;

a container;

an electrolyte;

wherein:

the first electrode, the second electrode, the porous separator, and the electrolyte are disposed in the container;

the first film is at least partially immersed in the electrolyte;

the second film is at least partially immersed in the electrolyte;

the porous separator is at least partially immersed in the electrolyte;

each of the first and second films include a mixture of carbon and binder wherein the activated carbon component has a soakability index of about 2 grams of electrolyte per gram of electrode material.

16. An electrochemical double layer capacitor in accordance with claim 15, wherein the soakability index is between about 1.38 grams of electrolyte/gram of electrode and about 2.2 grams of electrolyte/gram of electrode material.

17. The capacitor of claim 15, wherein the films are attached to respective collectors via a conductive adhesive layer.

18. A method for testing soakability, comprising the operations of:

- preparing an electrode sample containing an activated carbon component;
- cutting a controlled size electrode sample;
- measuring the thickness and weight of the cut electrode sample;
- weighing a sample of electrolyte solution;
- placing the electrode sample into the sample of electrolyte solution;
- allowing the electrode sample to soak for a controlled period;

- removing the electrode sample from the sample of electrolyte solution;
- weighing one or both of the electrode sample and sample of electrolyte solution; and
- determining the soakability of the electrode sample as a relation between the respective weights before and after the soaking operation.

19. A method according to claim 18 wherein the determining the soakability operation includes calculating the weight of the electrolyte soaked by the electrode sample per gram of electrode sample.

20. The method of claim 18, wherein the electrode sample contains one or more activated carbon types.

21. A method of making an active electrode material, the method comprising:
providing activated carbon;
providing binder; and,
mixing the activated carbon and the binder to obtain a mixture, wherein the activated carbon has a soakability index of at least about 1.38 grams of electrolyte per gram of electrode material.

22. A method in accordance with claim 21, wherein the soakability index is between about 1.38 grams of electrolyte/gram of electrode and about 2.2 grams of electrolyte/gram of electrode material.

23. An electrode comprising:
- a current collector; and
- a film of active electrode material attached to the current collector, wherein the active electrode material is a mixture including an activated carbon component, an optional conductive carbon component, and a binder component;
- wherein the activated carbon has a soakability index of at least about 1.38 grams of electrolyte per gram of electrode material.

24. An electrode in accordance with claim 9, wherein the soakability index is between about 1.38 grams of electrolyte/gram of electrode and about 2.2 grams of electrolyte/gram of electrode material.

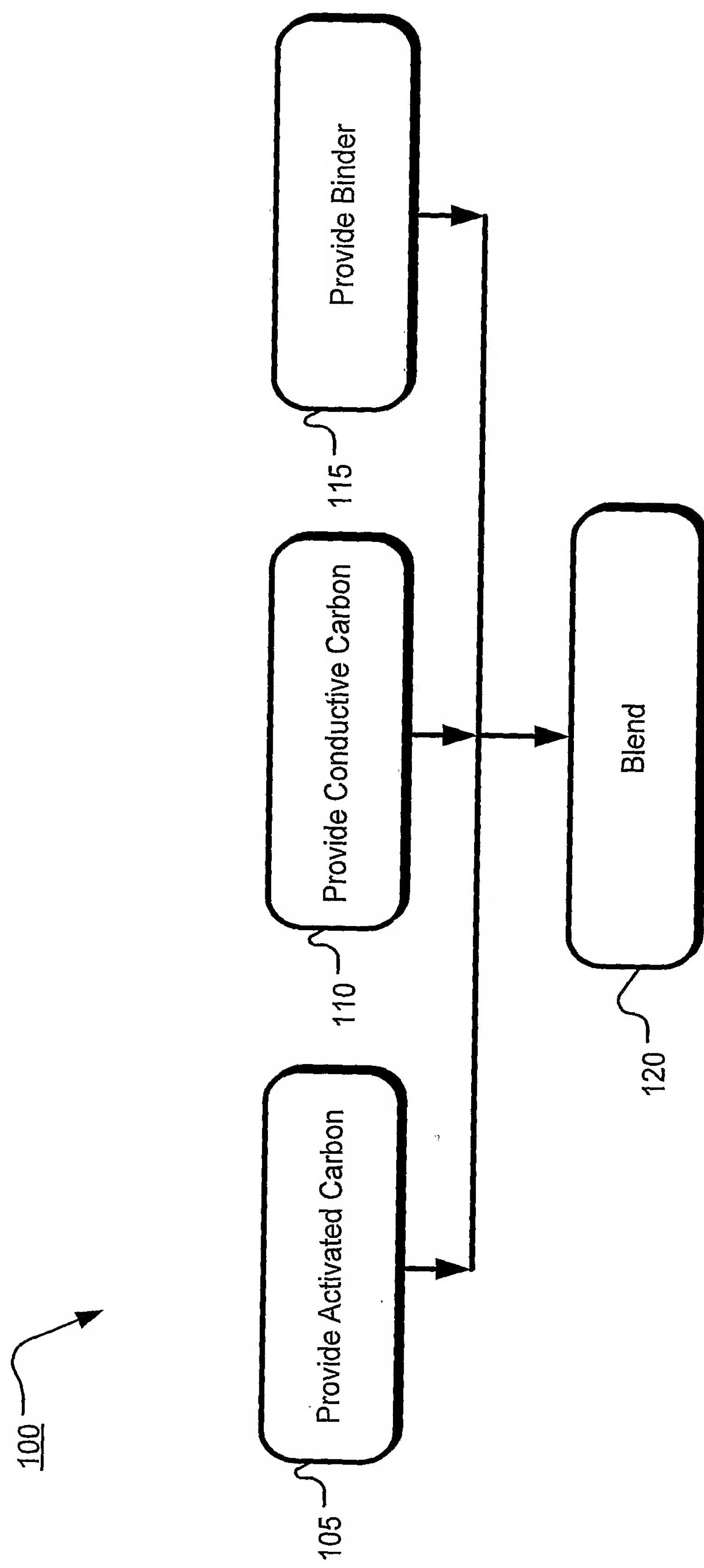


Fig. 1

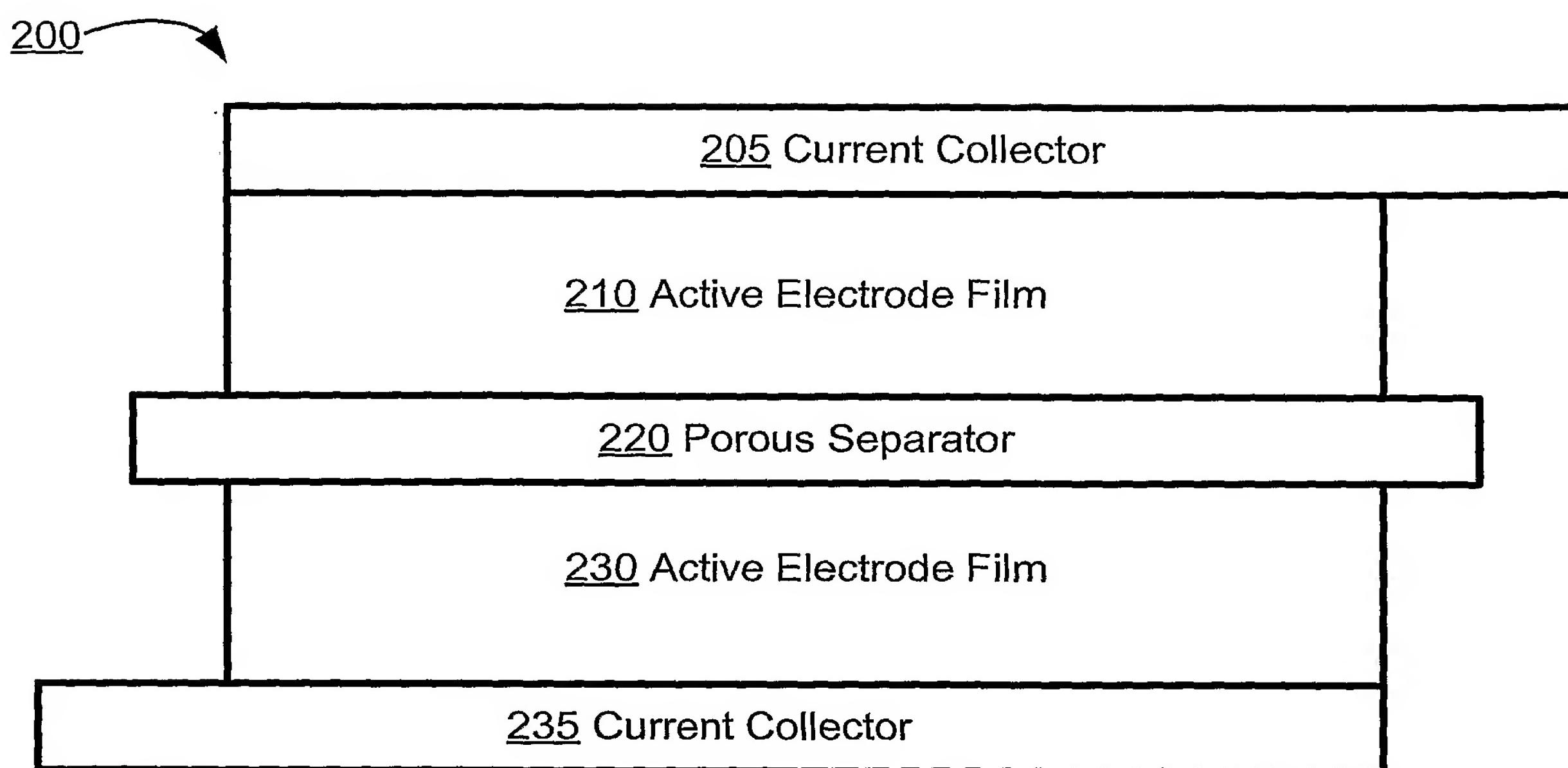


Fig. 2A

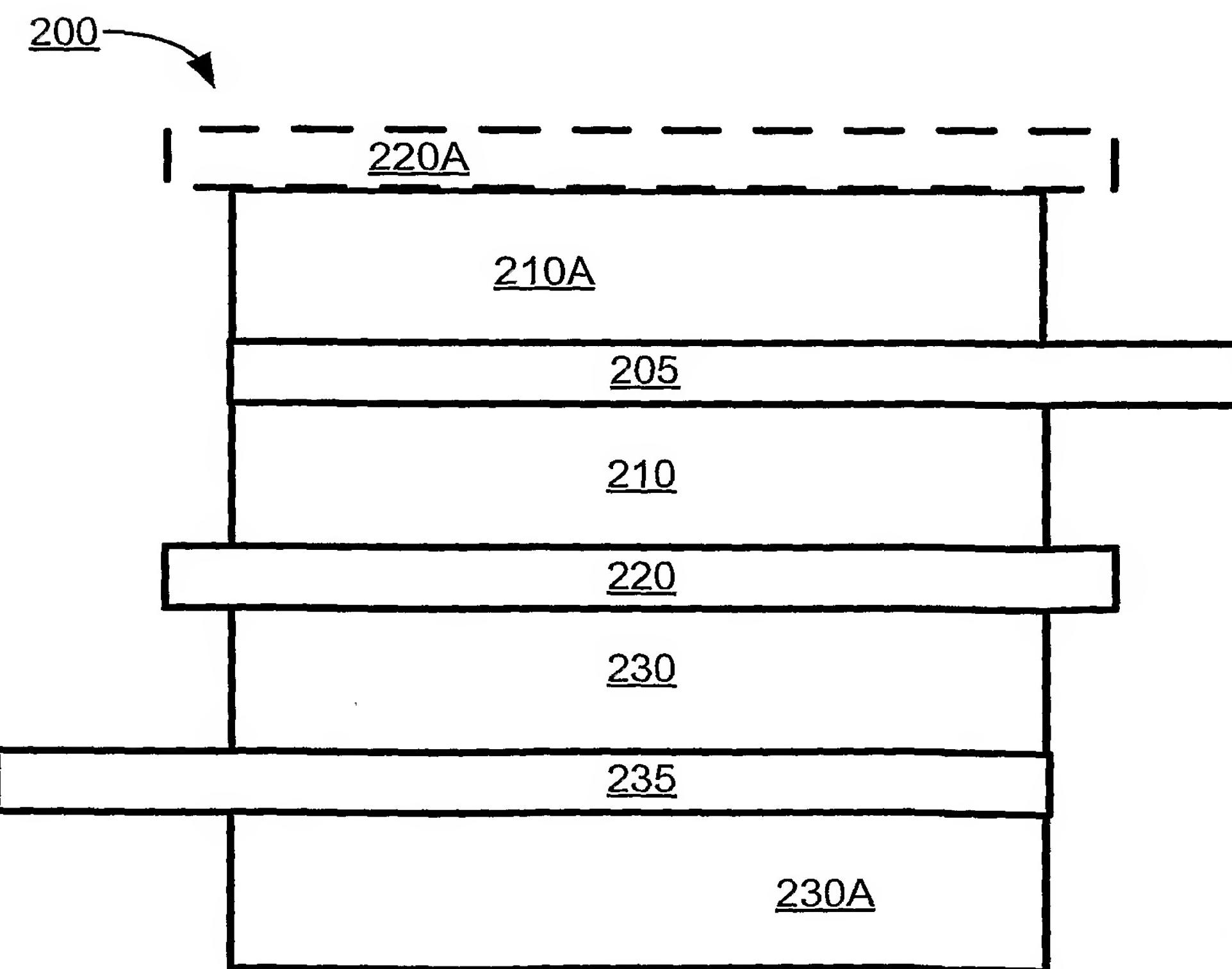


Fig. 2B

**Cap% fade during constant current cycling
@ 2.7V-RT, 15s rest**

300 →



Fig. 3

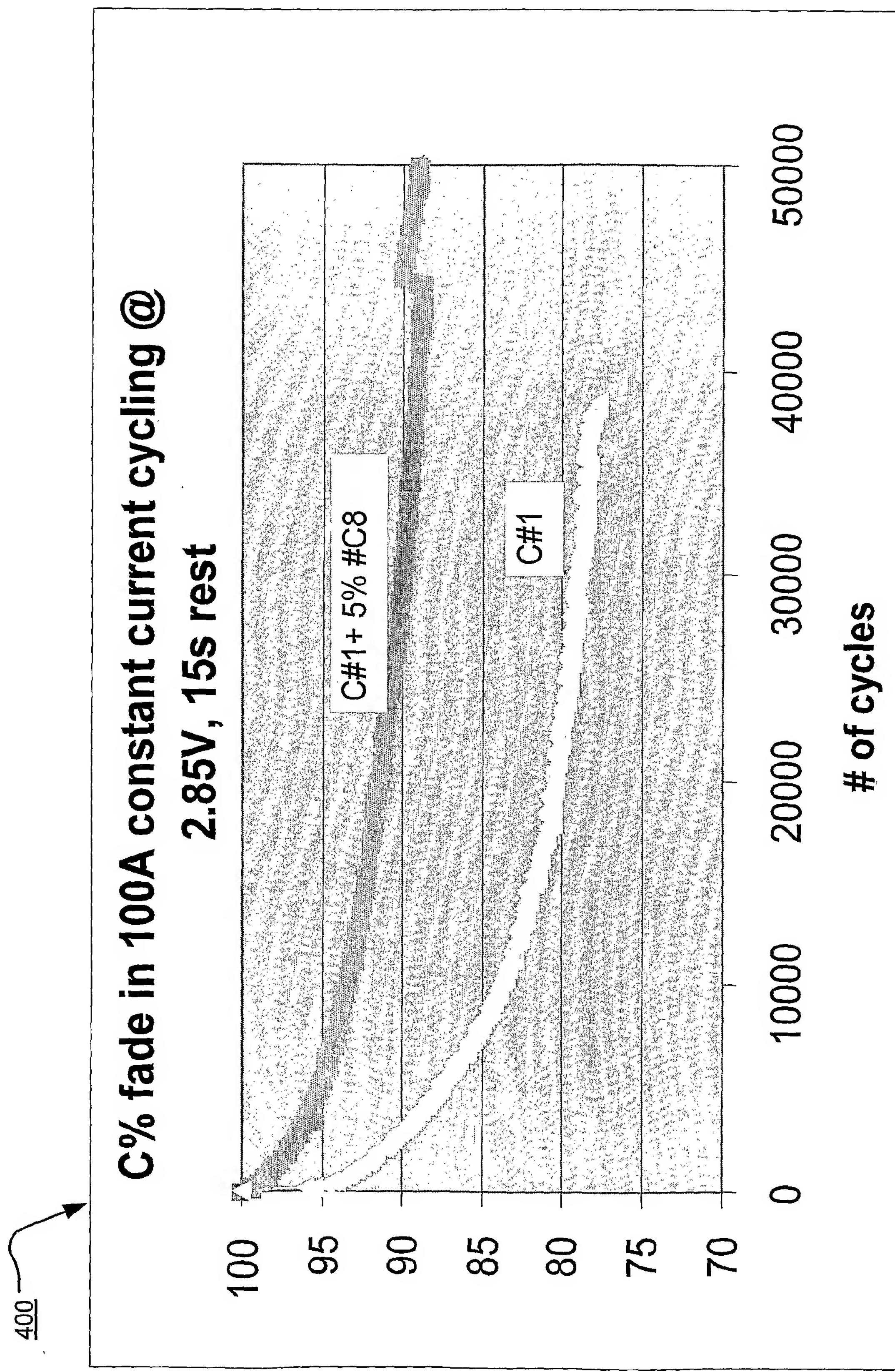


Fig. 4